The Annual Global Rare Earth Market was $5B in 2015 (~149,000 tonnes/yr)

The U.S. consumes around 11% ($550M) or ~16,000 tonnes/yr in 2015

The U.S. rare earth industry intermediate products (e.g., magnets, catalysts, ceramics, etc.) generated nearly $40B in revenue and 101,000 jobs (2013)

The U.S. rare earth industry end-market products (e.g., healthcare, communications systems, and defense technologies) generated nearly $260B in revenue and 433,000 jobs (2013)

The Majority of REE’s Imported into the U.S. Comes in As Finished Goods, and Not As a Raw Material

The U.S. imported $2.3T finished products containing REEs in 2015

The top 4 product groups – electronic equipment, machines, engines, pumps, vehicles, oil – account for ~50% of the imported value
REE Applications

**DEFENSE**
- Satellite Communications
- Guidance Systems
- Aircraft Structures
- Fly-by-Wire
- Smart Missiles

**CERAMICS**
- Capacitors
- Sensors
- Colorants
- Scintillators
- Reflectors

**PHOSPHORS**
- Display phosphors
- CRT, LCD, LED
- Fluorescents
- Medical Imaging
- Lasers
- Fiber Optics

**GLASS & POLISHING**
- Polishing Compounds
- Pigments & Coatings
- UV Resistant Glass
- Photo-Optical Glass
- X-ray Imaging

**METAL ALLOYS**
- NiMH Batteries
- Fuel Cells
- Steel
- Super Alloys
- Aluminum/Magnesium

**CATALYSTS**
- Petroleum Refining
- Catalytic Converter
- Fuel Additives
- Chemical Processing
- Air Pollution Controls

**MAGNETICS**
- Computer Hard Drives
- Disk Drive Motors
- Anti-lock Brakes
- Automotive Parts
- Frictionless Bearings
- Magnetic Refrigeration
- Microwave Power Tubes
- Power Generation
- Microphones & Speakers
- Communication Systems
- MRO

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NETL REE Website
Congressional Language

FY14 to perform an assessment and analysis of the feasibility of economically recovering rare earth elements from coal and coal by-product streams, such as fly ash, coal refuse, and aqueous effluents.

FY15 to continue activities to economically recover rare earth elements from coal and coal by-product streams, such as refuse, and aqueous effluents.

FY16-FY17 to expand its external agency activities to develop and test commercially viable advanced separation technologies at proof-of-concept or pilot scale that can be deployed near term for the extraction and recovery of rare earth elements and minerals from U.S. coal and coal by-product source showing the highest potential for success.
Challenges & Opportunities

- Currently U.S. does not produce REEs
  - Lack of a secure supply of domestic REEs results in risk to the U.S. economy and defense

- Off-shore production
  - Lower labor costs and lax environmental regulations
  - Production of primarily low commercial value, light REEs (L-REEs)

- What are the Barriers?
  - Relatively low concentration of REEs in coal and coal by-products, 100 - 1300 ppm (0.01-0.13 wt%) vs. commercial ores (monazite, bastnasite, etc.) which are typically 2 - 20 wt% (2,000-20,000 ppm) total REEs, makes recovery from coal-based sources technically challenging

- U.S. coal contains significant amounts of REEs
  - Appalachian coals represent the richest REE resources in the country
  - 208 coal preparation plants in WV, KY, P, VA, AL, TN with an installed capacity of 166,495 tons per hour, or more than one billion tons annually
  - Retrofitting only a portion of these plants with advanced REE separation processes would suffice the U.S. domestic need

Assessment of Rare Earth Elemental Contents in Select United States Coal Basins, Tetra Tech, January 2015
DOE-NETL Rare Earth Element Program

Key Drivers

• National Security
• Environmental Impact
• Economic Targets
• Build U.S. Domestic Infrastructure for On-Shore Production

|------|------|------|------|------|------|------|------|------|

DOE-NETL REE Program Portfolio

15 ACTIVE PROJECTS

• FY15-FY17 Research & Innovation Center (R&IC) Field Work Proposal (FWP) – Rare Earth Elements for Coal and Coal By-Products

• FY15 FOA DE-FE-0001202 – Opportunities to Develop High Performance, Economically Viable, and Environmentally Benign Technologies to Recover Rare Earth Elements (REEs) from Domestic Coal and Coal Byproducts

• FY16 RFP DE-SOL-0009067 – Identification and Characterization of Domestic U.S. Coal and Coal By-Products Containing High Rare Earth Element (REE) Concentrations

PROJECTS UNDER REVIEW FOR SELECTION

• FY16-FY17 FOA DE-FE-0001627 – Production of Salable Rare Earth Elements from Domestic U.S. Coal and Coal By-Products
REEx Separation & Extraction

Mining
- Ore
- Coal
- Shale
- Clay
- Fly Ash
- Recycled Materials

Physical Beneficiation
- Crushing
- Screening
- Regrinding
- Magnetic, gravity, electrostatic Separation

Leaching
- Hydrochloric Acid
- Sulfuric Acid
- Nitric Acid
- Caustic Cracking
- Acid Bake
- Calcination

Impurities Removal
- Thorium Precipitation
- Uranium Extraction
- Iron Extraction

Concentration of REO
- Ionic Liquid
- Solvent Extraction
- Carbonate Precipitation
- Ion Exchange
- Rare Earth Salts
- Carbonate Precipitation

Separation of REO
- Affinity Chromatography
- Electrophoresis
- Glass Production
- Permanent Magnets
- Battery Production
- Automobile Manufacturing
- Ceramics, etc...

Reduction to a Metal
- Concentrated REO to Rare Earth Metal
- Automobile Manufacturing
- Ceramics, etc...

Alloying, Products & Component Production
- Concentrated REO to Rare Earth Metal
- Automobile Manufacturing
- Ceramics, etc...

Final Technology

Feedstock Materials
- Run-of-Mine Coal
- Overburden & Underlying Clays/Shales/Sediments
- Coal Prep Plant Refuse
- Power Generation Ash
- Acid Mine Drainage Sludge

Run-of-Mine Coal
Overburden & Underlying Clays/Shales/Sediments
Coal Prep Plant Refuse
Power Generation Ash
Acid Mine Drainage Sludge

Zircon
ZrSiO₄

Monazite
(Ce, La, Nd)PO₄

Xenotime
YPO₄

 Courtesy of NETL R&IC
**FY15-FY17 NETL R&IC FWP Accomplishments**

- **Field Resource Assessment**
  - 768 field samples from PA & WV were collected in collaboration with FE-HQ and analyzed
  - Thorium spectral gamma-ray indicated the presence of REE-rich zones
  - H-REE association with Zr, Y, Hf
  - L-REE correlation with Th
  - Samples with high REEs appear to contain physically weathered monazite grains
  - Ti/Al correlates strongly with REE and indicates REEs were concentrated during periods of high erosion
  - Expanded field sampling: EPRI & USGS (MOAs); Consol
  - Luminescence-based fiber optic probe detects REEs at ppm levels (*Patent Application*)

Courtesy of NETL R&IC
FY15-FY17 NETL R&IC FWP Accomplishments

• Separation & Extraction Technologies
  • Regenerable immobilized amine sorbents for REE and heavy metals recovery from liquid sources — near 100% removal (Patent Application)
  • Organo-clays for recovery of rare earth elements — ~ 100% removal (Patent Application)
  • Physical separations – Achieved ~ 6,000 ppm REE pre-concentrate from 300-500ppm REE coal-based material
  • Thermal — ~ 100% removal from synthetic slags (Patent Application)
  • Development of multiphase CFD tools to simulate and optimize REE ammonium sulfate separation processes

• Techno-Economic Analyses
  • Models developed for assessing the performance and economics for REE separation & extraction
  • Established an in-house resource for global REE processing and market information
  • Identification of system and market knowledge gaps in coal-based REE recovery processes

![NETL Amine-Based Sorbent Uptake from Synthetic Acid Mine Water](image)
Opportunities to Develop High Performance, Economically Viable, and Environmentally Benign Technologies to Recover Rare Earth Elements (REEs) from Domestic Coal and Coal Byproducts

- Identify innovative processes using existing separation technologies for recovery of REEs from coal and coal by-products

- The resulting total concentration of mixed REEs in the final product from the proposed recovery process should approach 2wt% total REE

- The process designs proposed should minimize or reduce the environmental, safety, and health impact of radioactive and other byproducts, and optimize the overall economics of the separation and recovery process

5 Bench-scale projects & 4 Pilot-scale projects

Effort initiated March 1, 2016
Phase 1: 18 months
Competitive down-select
Phase 2: 18 month bench-scale
Phase 2: 30 month pilot-scale

— Accomplishment —
Within the first 6 months of project initiation, production of >2wt% REE pre-concentrates from coal-based materials was achieved
— TEAs being addressed —
FY16 RFP DE-SOL-0009067

Identification and Characterization of Domestic U.S. Coal and Coal By-Products Containing High Rare Earth Element (REE) Concentrations

- The objective is to identify, locate, field sample, and chemically analyze U.S. domestic coal and coal by-product solid and/or liquid materials that contain high rare earth element (REE) concentrations (i.e., ≥300 ppm total REE)

- Materials from the Illinois Coal Basin, Northern Appalachian Coal Basin in Pennsylvania and West Virginia, Central Appalachian Coal Basin in West Virginia, and the Raton Basin in Colorado and New Mexico

5 projects
Effort initiated October 1, 2016
Period of performance: 18 months
Production of Salable Rare Earth Elements from Domestic U.S. Coal and Coal By-Products

- Achieve small-scale production of salable REEs in the form of final products such as individual rare earth oxides (REO) and/or other individual rare earth compounds
  - Small-scale is defined as a minimum composite rare earth output of 10 pounds per day (reported as oxides)
- REE production is at least three individual rare earth elements (REEs), preferably heavy REEs, as compounds with sufficient purity to render them salable in the marketplace, at a minimum 90%-99% purity
- Process feedstocks (pre-combustion coal and coal by-products) may include run-of-mine coal, overburden and underlying materials and partings/sediments associated with coal seams, coal preparation plant refuse and other by-products, and acid mine drainage sludges

<table>
<thead>
<tr>
<th>Rare Earth Element</th>
<th>Metal Market Price $/kg</th>
<th>Oxide Market Price $/kg</th>
<th>Major Use</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr</td>
<td>$80.00</td>
<td>†$50.06</td>
<td>Permanent Magnets, LaNiH Batteries, Phosphors</td>
<td>Magnets for Wind Turbines Hybrid Vehicle Batteries Computer Hard Drives Mobile Phones Medical Scanners Power Tools</td>
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<tr>
<td>Nd</td>
<td>$50.00</td>
<td>†$39.05</td>
<td>Permanent Magnets, LaNiH Batteries, Catalysts, Glass Additive</td>
<td></td>
</tr>
<tr>
<td>Eu</td>
<td>*$1,600.00</td>
<td>‡$66.00</td>
<td>Phosphors, Fiber Optics</td>
<td>LCD’s LED’s Fluorescent Lights</td>
</tr>
<tr>
<td>Tb</td>
<td>$564.00</td>
<td>§$425.00</td>
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<tr>
<td>Dy</td>
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<td>§$187.00</td>
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<td>$34.00</td>
<td>‡$3.67</td>
<td>Phosphors, Coatings</td>
<td>Gas Turbine Thermal Barrier Coatings</td>
</tr>
</tbody>
</table>

*2003 Market Prices per Rare Elements Resources 2004 Report
** September 2016 Market Prices per mineralprices.com
† Converted from tonnes to kg
‡ 2013 Cumulative Revenues per Rare Earth Technological Alliance 2014 Report
FY16-FY17 Review Meetings & Workshops

NETL-HQ REE Workshop
NETL Morgantown
August 8-9, 2016

Purpose:
- To accelerate REE technology research development, demonstration and deployment for separation of REEs from coal and coal by-products, the REE Workshop was hosted by NETL in support of DOE FE-HQ.
- Provide an open forum for industry, university, government agencies to discuss potential opportunities and/or research requirements to address accelerated achievement of REE recovery in a techno-economic and benign manner by 2023-2025.
- Further announce the release of Funding Opportunity DE-FE-0001627, and address questions relative to responding to the FOA.

102 Registered Participants

Success Outcomes
- Networking across the REE Value Chain – Open discussions
- Workshops requested with government leaders
- State-of-the-art technology discussions – Genesis of materials formation
- Comparison of coal vs alternate feedstocks for REE production
- Government – Private investment – Industry roles
- Research needs for success
- Feedstock dependency – Basic analyses of resources/Approach for predictive prospecting
- Grinding kinetics for REE liberation & separation
- Commercial aspects & risks
- Schedule – Facility vs product definition & quantity produced; Production and market entry

2016 Project Review Meeting
for Crosscutting Research and Analysis and Rare Earth Elements
REE Project Portfolio Poster Session
Station Square, Pittsburgh, PA
April 18, 2016

2017 Project Review Meeting
for Crosscutting Research and Analysis, Gasification Technologies, Rare Earth Elements Research Portfolios
Omni William Penn, Pittsburgh, PA
March 22, 2017
**Acnowledgments**

**NETL Technology Development & Integration Center (TD&IC)**
- Pat Rawls
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- Rick Dunst
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**Legal**
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- Patent
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**Public Affairs**
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  - Bill Garber
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  - Matthew Fortner
  - Robert Thompson
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  - Duane Miller
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  - Jennie Stoffa
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- Blackhawk Mining
- BRC Refining
- Rick Honaker
- Roe-Hoan Yoon
- Aaron Noble, Jim Hower,

**Physical Sciences Inc.**
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- Prakash Joshi
- John Groppo
- James Hower

**Southern Research**
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- Jay Renew
- Corey Tyness
- James Irwin
- Rod Vera
- Kevin Davis
- Josh Wendt
- Dave Wang

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- Steve Benson
- Daniel Palo, Ed Murphy

**University of Wyoming**
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- Morhong Fan
- Maciej Radosz, Hertanto Addiharma, Hanjung Tian
- Eric Williams, Gabrielle Gaustad

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- Rick Honaker
- James Howe
- Cortland Eble

**West Virginia University, Water Resources Research Institute**
- Paul Ziemkiewicz

**XLight Corporation**
- Robert Uhrin
- David Uhrin

**Tetra Tech Inc., Pennsylvania & Colorado**
- Farley Woods
- Tom Gray
- Katherine Pugh
- Jessica Moore

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**NETL Science & Technology (S&T)**
- Mary Anne Alvin
- John Wimer

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**RARE EARTH ELEMENTS FROM COAL AND COAL BY-PRODUCTS**

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- Mary Anne Alvin
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**NETL**
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- Doug Hollett
- Angelo Kokkinos
- Regis Conrad
- Pete Rozelle
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http://www.netl.doe.gov/research/coal/rare-earth-elements/

https://edx.netl.doe.gov/ree/